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# Water desalination using humidification / dehumidification unit integrated with waste heat and induction heating system

***Hatem E. Nasr[1*], Khaled Ramzy[1], Tamer Mansour[1], Mohamed M. Khairat Dawood[2], A. E. Kabeel[3]***

*[1]Department of Mechanical Engineering, Faculty of Engineering, Suez Canal University, Ismailia, Egypt.*
*[2]Department of Mechanical Power Engineering, Damanhur University, Egypt.*
*[3]Department of Mechanical Power Engineering, Tanta University, Egypt.*

**Corresponding author: Hatem E. Nasr, Email address: hatem.elhuseen@eng.suez.edu.eg*
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## Abstract

*The desalination system by humidification and dehumidification has shown great success in desalinating highly saline sea water , This system is also characterized by the high quality of the water leaving it, where the percentage of pollutants and salts in the water was almost non-existent. In the implemented HDH system, the air enters through a blower into the duct and passes over the condenser of the cooling system, so the air temperature increases and the condenser temperature decreases, which enhances the efficiency of the dehumidifying unit. The air temperature is more, then the hot air passes over the humidification unit, where the salt water is sprayed at high temperatures, which increases the percentage of air humidity, as the air carries a high percentage of water vapor, and a portion of the highly saline water remains, which is discharged through the drain, in The final stage, the air loaded with water vapor passes over the dehumidifier, and a large part of the water vapor condenses and is collected in the desalinated water tank he system reaches its highest water production of 17.64 L/hr at an air flow rate of 504 kg/hr with a fully open setting. With a fully open setting and 504 kg/hr air flow, the system produces around 141.1 L of fresh water per day, significantly more than the 55.6 L produced with a 252 kg/hr air flow. This configuration yielded a local water production of 17.64 liters per hour, with a production cost of 0.029 dollars per liter.*

**Keywords:** *desalination; humidification and dehumidification; waste heat; refrigeration; induction heating system.*

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## 1. Introduction

Water covers a substantial amount of the earth's surface and is vital to all living things. Despite the fact that water covers the bulk of the planet, the majority of the world's countries lack adequate drinking water. Desalination is a frequent method for producing drinking water in locations when the only available water sources are seawater or brackish. Modern desalination procedures used with brackish and seawater have proven to be efficient alternatives in a range of conditions. The humidification and dehumidification desalination system has proven to be extremely effective in desalinating highly saline sea water; this system is also differentiated by the exceptional quality of the water it produces, with nearly no contaminants or salts. Because most of these procedures demand a significant amount of energy, employing renewable energy for desalination through humidification and dehumidification is recognized as the most important and cost-effective method of producing drinkable water. Several studies are being conducted to increase the production of drinking water and the efficiency of these systems. Kabeel and El-Said (Kabeel, et al, 2013) investigated various configurations of solar-powered hybrid air humidification and dehumidification-single stage flashing (HDH-SSF) desalination systems. The results revealed that the solar air heater combined with a hybrid system had the greatest economic pattern, generating up to 96 liters of water per day at a cost of \$12.53 /m2. Li et al. (Li, et al, 2014) conducted research on a humidification and dehumidification desalination system that used evacuated tubes solar air heaters. The humidifier and dehumidifier were built utilizing mathematical design methods. The testing findings revealed that spraying different input water temperatures in the pad humidifier from 9 °C to 27 °C increased the relative humidity of exit moisture from 89% to 97% and the air temperature at the outlet from 35 °C to 42 °C. Amin et al. (Amin, et al, 2015) investigated the performance of a pilot solar desalination system incorporating a solar-aided heat pump and a single-effect evaporator unit. The system's performance had been evaluated and analyzed using sun irradiation and compressor speed. The results showed that the performance ratio ranged from 0.43 to 0.88, and the average coefficient of performance was approximately 8, with a maximum productivity of 1.38 kg/h. Attia (Attia, et al, 2016) conducted an experimental study on a heat pump seawater distillation system using a passive vacuum generation technology. The proposed system was designed by lowering the saturation temperature of seawater to fit the operational temperature ranges of various refrigerants. The results showed that the coefficients of performance reached 8, 9, and 7.5 at the optimal saturation temperature of 5 °C. Siddiqui et al. (Siddiqui, et al, 2016) designed and built a solar humidification-dehumidification desalination system that included a centrifugal air blower. The system was connected to a humidification chamber that included two electric water heaters and a condenser. The results showed that the daily productivity and gained production ratio increased by up to 57%. Tariq et al. (Tariq, et al, 2018) designed an air saturator in the wet channel of a desalination humidification-dehumidification system by combining an infiltration flow from the dry to the wet passages of the air saturator. The results showed that the system increased fresh water production by 30%, recovery ratio by 46%, and gain-output ratio by 11%. Lawal et al. (Lawal, et al, 2018) investigated theoretically a humidification-dehumidification system with heat pump support. The heat from the system's condenser was utilized to raise the temperature of the saltwater before it entered the humidifier, and the evaporator absorbed heat from the water fed into the dehumidifier. The results revealed that the maximum possible gain output ratio was roughly 8.88 and 7.63 at 80% component effectiveness and mass flow rate ratios of 0.63 and 1.3, respectively.

El-Maghlany et al. (El-Maghlany, et al, 2018) investigated a two-stage dehumidification water desalination system. The condenser of the heat pump had been used in the system in order to enhance the moisture absorbing capacity of air. Water was sprayed at a constant flow rate of 2.2 l/min using cross, counter, and parallel flow spraying systems. The results showed that, the parallel flow spraying system had the highest output in both single and two stage dehumidification, with productivity of 2.34 and 4.44 l/h. He et al. (He, et al, 2018) numerically examined a humidification-dehumidification-desalination system with a mechanical heat pump. The simulation results showed that the system performed optimally at the balance condition of the dehumidifier, with 82.12 kg/h of water productivity and a gain output ratio of 5.14. Santosh et al. (Santosh, et al, 2019) used TRNSYS software to investigate the theoretical feasibility of a hybrid humidification-dehumidification desalination system powered by waste heat from a vapor compression refrigeration unit. The theoretical results show that the suggested model can be used to design and forecast the behavior of a desalination unit under a variety of climatic conditions. Finally, the cost of producing freshwater from the system was around \$0.1658 per kilogramme. Abbady et al. (Abbady, et al, 2020) improved the performance of a humidification-dehumidification system by implementing three distinct modified cycles. The experimental results demonstrated that the fins cycle increases productivity, gain output ratio, recovery ratio, and exergetic efficiency by 18%, 12.33%, 13.73%, and 15.9%, respectively. Lawal et al. (Lawal, et al, 2020) studied experimentally a humidification-dehumidification system for water desalination and space conditioning driven by heat pump. The results concluded that, the system was able to reach the max gain output ratio of 4.07, coefficient of performance of 4.85, recovery ratio of 4.86%, and water productivity of 287.8 l/day and energy utilization factor of 3.04. Anand and Murugavelh (anand and Murugayelh, 2020) studied the performance of new design with modified vapor compression refrigeration coupled with humidification-dehumidification desalination system. The results concluded that, the maximum productivity and cooling output are 7.35 l/h and 1.89 kW respectively with coefficient of performance, gained output ratio, energy utilization factor and cost of desalination of 2.16, 6.11, 8.27 and 0.0096 $/L respectively. Sachdeva et al. (Sachdeva, et al, 2020) demonstrated numerical model by MATLAB code for a solar humidification-dehumidification desalination system with waste hot air from an air conditioner and compare the results of the proposed system with the conventional system. The results showed that, usage of hot air from an air conditioner's condenser with mass flow rates of 0.032 to 0.035 kg/s enhanced the productivity by 21% to 31% every day. Shalaby et al. (Shalaby, et al, 2021) tested a hybrid solar desalination humidification and dehumidification system. The results showed that utilizing a solar reflector lowered daily electrical energy use by 16.5%. Mohamed et al. (Wang, et al, 2021) employed a closed-air cycle to improve a solar humidification and dehumidification water desalination system. The obtained results demonstrated that at water temperatures of 40°C, 50°C, 60°C, and 70°C, respectively, the gain output ratio improved with an average value of 0.71, 0.74, 0.78, and 0.81, and productivity reached 1.46 kg/h, 2.59 kg/h, 4.40 kg/h, and 6.99 kg/h. Wang et al. (Abu El-Maaty, et al, 2021) created a solar vacuum desalination system complete with an interior condenser. The system performance was evaluated under actual weather conditions using an 18 m2 flat-plate solar collector. The trial findings revealed that the daily productivity was around 154.14 kg and the performance ratio was 1.36 at an average solar radiation of 672 W/m2. Abu El-Maaty et al. (Mohamed, et al, 2021) conducted experiments on a fog desalination system powered by an evacuated tube solar water heater. The experimental results revealed that the recommended operational inlet water temperature for the desalination system is greater than 55 °C based on salinity tests. Abdelaziz et al. (Abdelaziz, et al, 2022) investigated a solar desalination system using a high-frequency ultrasonic atomizer as a humidifier to attain 100% relative humidity. The experiment findings showed that raising the number of atomizers to 6 and lowering the water height to 1 cm increases the daily water productivity. Rafiei et al. (Rafiei, et al, 2022) explored a hybrid energy conversion system, evaluating exergy, energy, and environmental parameters for producing power and freshwater. Many working fluids, including Al2O3, Cu, CuO, TiO2, and MWCNT nanoparticles in oil as the base fluid, were employed. The obtained results suggested that the freshwater productivity ranged between 15.28 kg/h and 15.46 kg/h with the use of Nano fluid. From the previous review, it can be deduced that, the productivity of a humidification-dehumidification system is determined by the dehumidifier cooling water flow rate, the saline water temperature at the humidifier's inlet, the solar intensity, and the air flow rate. The combination of HDH systems with power plants or geothermal energy was effective in terms of performance and evaluation. Solar collectors and PV/T could efficiently power HDH systems in off-grid areas.

The use of hot air from the air conditioner's condenser increased productivity from 21% to 31% per day. Furthermore, increasing the temperature of the water in the dehumidifier outlet allows for the reduction of exergy losses in the dehumidifier and the use of the high frequency ultrasound atomizer and the water height with hot air stream flow rate on productivity, while decreasing water height leads to an increase in daily productivity. We have developed the HDH system so that the system's productivity is higher than the rest of the systems, the HDH system has been provided with an air conditioning unit and a heating unit for air and water working with oil through electromagnetic induction heaters where the air passes through the condenser of the air conditioning unit, which works on heating Air and ferion cooling and then passing through the oil heating unit, which increases the air temperature to reduce the relative humidity of the air, at the same time the hot oil passes through water heaters and works to raise the temperature of the water to be desalinated before the spraying process, After that, hot water is sprayed on the air coming out of the heating unit to humidify the air in the humidifier After that, the air loaded with water vapor passes over the dehumidifier unit, which is the evaporator of the air conditioning unit, which works to condense the fresh water and remove moisture from the air . It is noticeable during the experiment that the maximum production amount of fresh water is the Ideal conditions for the highest production efficiency of the device at the temperature of the sprayed water is "70 degrees Celsius" and at a rate of "4 liters per minute" and also at an air flow rate of "420 cubic meters per hour", so the amount of fresh water is "17.64 liters per hour" and It has a higher "GOR = 2.98".
The aim of the study outlined in the document is to evaluate and enhance the performance of a humidification-dehumidification (HDH) desalination system by utilizing waste heat from a refrigeration unit and incorporating a secondary induction heating system. The primary objective is to optimize the desalination process to maximize freshwater production efficiency under various operational and environmental conditions. This study focuses on identifying the ideal operational parameters—such as air and water flow rates, and temperature settings—to achieve the highest freshwater output with minimal energy consumption. By experimenting with different system configurations and utilizing renewable energy sources, the research aims to provide a sustainable, cost-effective solution for desalinating highly saline water, thereby contributing to alleviating water scarcity challenges.

## 2. Experimental setup

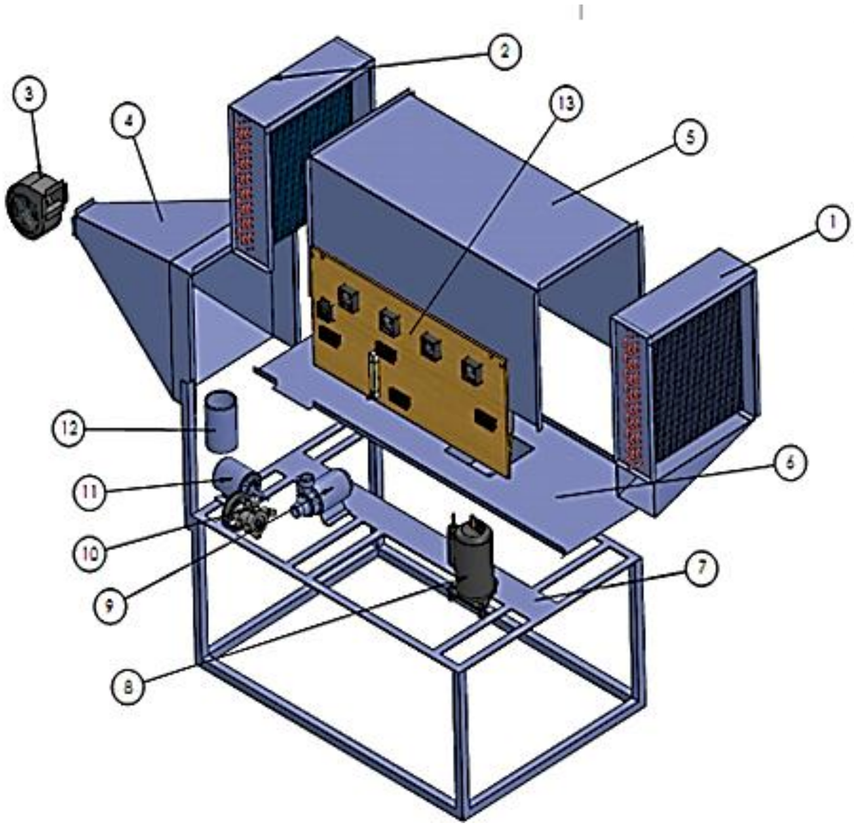
The present experimental setup of the humidification – dehumidification device was designed, installed and tested in Energy Laboratory, Department of Mechanical Engineering, Faculty of Engineering, Suez Canal University, Ismailia city -Egypt during the period of July 2022. Figure 1 illustrate the schematic diagram of introduced system while Figure 2 shows a photo of experimental device. The layout of the experimental. The idea of the device is to desalinate salt water by humidifying the air and then dehumidifying it through cooling and heating systems, taking advantage of the waste heat from the cooling system and increasing the humidification efficiency by heating the air, as well as the salty spray water, respectively. The device consists of five main units working in parallel (refrigeration unit, secondary air heating unit, air humidifying, air control unit and control and monitoring panel), and all these five systems were assembled on one iron base.

### 2.1. The refrigeration unit

The refrigeration unit consists of (condenser, evaporator, compressor, throttle valve, electric capacitor, Freon, and N-shaped copper tube). This unit basically works on preheating the air by passing it through the condenser and then cooling the air saturated with water vapor to dehumidify it by passing it through the evaporator. The COP of the compressor is 3.20 and it has a cooling capacity of (5.275 W) and therefore the heat emitted from the condenser is equivalent to (6925 W). The condenser and evaporator of the unit are essential parts of the HDH system and both of them consists of aluminum fins, copper tubes and elbows. The function of condenser is to cool the compressed refrigerant gas and to perform a sensible heating of the air entering the device taking advantage of the lost heat from cooling the refrigerant gas. The function of evaporator is to provide space to refrigerant gas to expand in it for cooling. Therefore, the evaporator in the HDH system works as a dehumidifier so that it reduces the temperature of the air passing through it in order to removes moisture from it.

### 2.2. Humidifier

The air humidifier system is a system that raises the content of water vapor in the air or works to saturate the air with water, and depends on spraying hot water through 12 nozzles so that the water spray covers the section area of the duct. This system works with an efficiency of 60%. This system consists of several main parts (nozzles, water pump, circular copper pipe, flow rate control valve, metallic connections, silicone hose and water tank). The water pump supplies water to the nozzles at a pressure of 5 bar continuously. The capacity of the water pump is 0.5 HP, which is equivalent to approximately 370 W, with a maximum flow rate 0.6 m3/h. Circular copper tube, on which the nozzles were distributed regularly to ensure that the area of the duct section area was covered with water spray, it has an average length 2 m, where the M5 nut were welded to the pipe in order to fix the nozzles with it, and a half-inch copper tooth was also welded to the entrance to the pipe, and the end of the pipe was sealed to ensure that the amount of water passes through the nozzles only. The flow rate valve is a valve that controls the amount of water that is sprayed or supplied per minute manually. The valve has been calibrated to give 5 quantities of flow rate, which are 1, 1.5, 2, 3 and 4 l/ min liters per minute. Figure 3 shows the different components of modifier system.




| PART NUMBER | PART NAME |
|---|---|
| 1 | Evaporitor |
| 2 | Condenser |
| 3 | blower |
| 4 | semi-conical front |
| 5 | upper cover |
| 6 | floor |
| 7 | Chassis |
| 8 | compressor |
| 9 | water pump |
| 10 | oil pump |
| 11 | driver |
| 12 | oil tank |
| 13 | Monitoring Panel |

**Figure 1: Schematic diagram of the experimental setup.**

**Figure 2: Photograph of the experimental setup.**

### 2.3. Oil-heating system

The oil heating unit performs two tasks, Firstly, Heating the air inside the duct using a heat exchanger and secondly Heating the water of the humidifier This unit consists of several main parts (four induction heaters with 1.2 kW total power, oil pump, driver motor, oil-air heat exchanger, high pressure hoses, return valve, T-junction, belt, flow meter, oil-water coil, adjustable Screw Bolt Clamps, oil tank and hydraulic oil). The functions of induction heaters are to heating the air through the oil – air heat exchanger and to heat the feed water through oil - heating coils. Table 1 shows the specification of oil pump.

**Table 1. Oil pump specification table**

| | |
|---|---|
| **Operation speed** | 475 rpm |
| **Operation pressure** | 6 bar |
| **Usable flow rate** | 0.33 l/m |
| **Total operation flow rate** | 1.2 l/m |
| **Working temperature** | 10 to 130 C |
| **Maximum speed** | 6000 rpm |
| **Maximum pressure** | 90 bar |

### 2.4. Air control unit and duct

The necessary air is supplied to the device through a blower, where it is installed on the inlet of the duct. The blower was also provided with a variable inlet opening to control the amount of distraction entering the system. Table (2) shows the blower specifications. The duct is a casing made of galvanized sheet that includes water sprayers, condenser, evaporator, oil-air heat exchanger and blower; duct is responsible for controlling the direction of the air and controls the operations that take place on the air. The duct is made up of four pieces, which are the floor, the upper cover, the distilled water collector and a semi-conical front. The duct is made of galvanized sheet with a thickness of 0.5 mm, due to its good resistance against corrosion from salt water, the duct parts were also assembled with screws and silicone to ensure that air does not leak between the links. The silicone used is refractory silicone to withstand high temperatures during operation. The duct is also equipped with a glass detection hole to follow the system from the inside, where a thermal glass was used to withstand the system temperatures inside the duct. The duct is covered from the outside with glass wool, in order to isolate it from the surrounding air, which maintains its temperature from the inside and prevents water condensation on the duct walls. The floor is equipped with two drums in the middle, where the brine is collected and then sent to the feeding tank to be sprayed again.

**Table 2. specification of blower.**

| | |
|---|---|
| **CFM** | 420 m3 / hr |
| **Power input** | 120 W |
| **Input voltage** | 220 to 230 V |
| **Weight** | 3.2 kg |
| **Speed** | 2600 rpm |

### 2.5. Control and monitoring panel

The control and monitoring panel is a part of the HDH system, through which all results are monitored and the induction heaters are closed and opened. It is a panel on which the temperature, humidity sensors and oil flow meter are installed, and the control switch for operating the induction heaters, and also the induction heaters and the power supply are installed on it as shown in Figure (3).

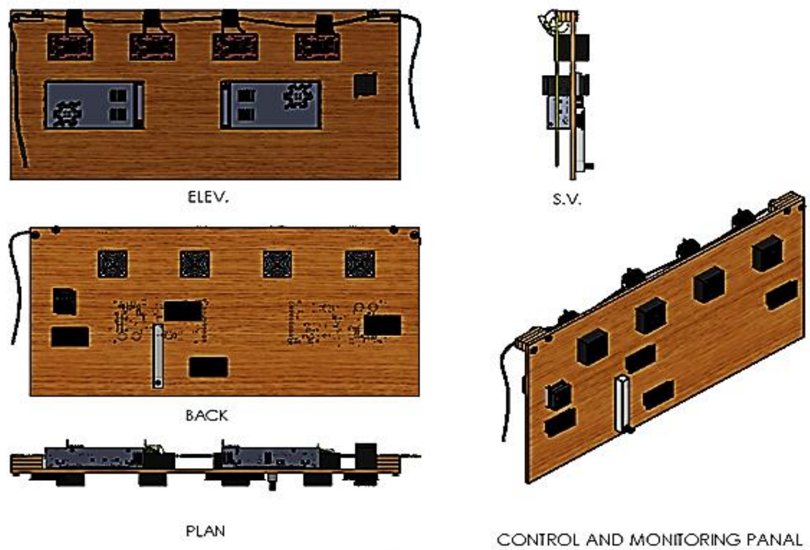



**Figure 3: Illustrative photos for the duct components.**

### 2.6. Photovoltaic solar cells

Photovoltaic solar cells are cells that convert sunlight into an electric current and there are 4 Photovoltaic solar cells with a total power output 1000W are used to supply electricity to the HDH device. The technical specification for solar cell used is illustrated at Table 3

**Table 3: Technical Specifications for solar cell**

| Parameter | Value |
|---|---|
| Model Number | STP265-20/Wfw |
| Rated Maximum Power (Pmax) | 265 W |
| Output Tolerance | 0 / +5 W |
| Current at Pmax (Imp) | 8.56 A |
| Voltage at Pmax ($V_{mp}$) | 31.0 V |
| Short-Circuit Current ($I_{sc}$) | 9.02 A |
| Open-Circuit Voltage ($V_{oc}$) | 37.8 V |
| Nominal Operating Cell Temperature (T NOCT) | 45°C ± 2°C |
| Weight | 18.3 kg |
| Dimensions | 1650 mm × 992 mm × 35 mm |
| Maximum System Voltage | 1000 V |
| Maximum Series Fuse Rating | 20 A |
| Cell Technology | Multi-Si |
| Application Class | A |
| Test Condition | AM = 1.5, E = 1000 W/m², Tc = 25°C |

### 2.7. The total cost evaluation of HDH system

Humidification-Dehumidification (HDH) systems are thermally-driven desalination systems that use solar energy as the primary source of power. These systems operate by evaporating water (humidification) and subsequently condensing the vapor to produce fresh water (dehumidification). The cost calculation for such a system involves capital expenditures (CAPEX), operating expenditures (OPEX), and the cost of water production (CWP). Table (4) shows the cost of each component of the humidification-dehumidification system. Below is a detailed outline of the cost calculation process, along with the relevant equations.

### 2.7.1 Capital Expenditures (CAPEX)

CAPEX includes the initial cost of all components and equipment necessary to set up the HDH system. The main components include solar modules, humidifier, dehumidifier, pumps and blowers and storage tanks

The total capital cost (Ccap) is calculated as (Al-Hallaj & Selman, 2002):

$$C_{cap}=C_{solar}+C_{humidifier}+C_{dehumidifier}+C_{pump}+C_{blower}+C_{storage} \quad (1)$$

### 2.7.2 Operating Expenditures (OPEX)

OPEX includes the costs associated with the operation and maintenance of the HDH system. These costs include;

- Maintenance costs, energy costs and labor costs.

The annual operating cost ($C_{op}$) can be estimated as (El-Agouz 2010):

$$C_{op}=C_{maintenance}+C_{energy}+C_{labor} \quad (2)$$

Assuming that $C_{maintenance}$ = 2% of CAPEX = \$550/year, $C_{energy}$ = \$0.05/kWh,
Assuming 1,000 kWh/year for auxiliary power = \$50/year and $C_{labor}$ = \$2,000/year
The annual operating cost will be $C_{op}$=550+50+2,000=\$2,600/year.

### 2.7.3 Cost of Water Production (CWP)

The CWP is calculated by dividing the total annual cost by the annual water production. The total annual cost includes both CAPEX and OPEX, amortized over the system's lifetime.

The amortized capital cost ($C_{amort}$) is given by (Kabeel & Abdelgaied 2017):

$$C_{amort}= (Q_{prod}\times CRF) /C_{cap} \quad (3)$$

Where:

- CRF = Capital Recovery Factor, which is calculated as (Manokar & Kalidasa Murugavel 2017):

$$CRF = r\,(1+r)^n / [(1+r)^n - 1] \quad (4)$$

r = Interest rate (e.g., 5% or 0.05), n = System lifetime (e.g., 20 years)

- $Q_{prod}$ = Annual water production ($m^3$/year)

**Table 4. Cost of component of HDH system.**

| Part | Price by $ |
|---|---|
| Compressor | 139 |
| Evaporator | 166 |
| Condenser | 166 |
| Throttle valve “capillary tube” | 6.6 |
| Copper tubes | 22.6 |
| Refrigerant “R-22” | 83.5 |
| Capacitor “45µf” | 8.5 |
| Nozzles | 21.6 |
| Circular copper tube | 25 |
| water pump | 22.2 |
| Flow control valve “stopcock” | 5 |
| Metallic connections and Silicon hose | 25 |
| Water tank | 5.5 |
| Oil pump | 27.9 |
| Oil pump base | 8.33 |
| Driver | 22 |
| The belt and induction heater | 85 |
| Oil - air heat exchanger | 22.5 |
| oil-water coil | 12.5 |

| | |
|---|---|
| Return valve | 4.5 |
| Oil flow meter and oil tank | 31 |
| Hydraulic oil | 12.5 |
| the connections | 27.7 |
| Air control unit | 66.6 |
| The Duct | 111.1 |
| Glass detection and temperature sensors | 80 |
| Duel humidity temperature sensors | 38 |
| on/off switch | 1.5 |
| Chassis and wires | 40 |
| Photovoltaic solar cells | 1000 |
| **Total** | **2286.8 $** |

## 3. Experimental procedure

The experiments were conducted from 7:00 a.m. to 10:00 p.m. through July 2022. The following parameters are measured during the experiments, the solar intensity, ambient temperatures (32.5 $^{o}$C dry bulb temperature), Relative humidity (39%), wind velocity (7 miles per hour), average temperature after condenser is (50C dry bulb temperature), average temperature after oil air heat exchanger (5450 $^{o}$C dry bulb temperature), average water temperature (70 $^{o}$C), and accumulated output water productivity is (17.64 L). Every hour, measurements are taken. All experimental measurements were designed to assess the performance of HDH system at ambient conditions of Ismailia City-Egypt. The experiments show that with the increase in the air flow rate, the productivity increases, due to ensuring good cooling of the condenser, as well as to ensure a greater load of the sprayed water, and also this increases the efficiency of the evaporator, which works to condense the largest possible amount of water. The rate of spraying water increases the saturation of the air with water, which increases water productivity, it is also noted that the less air flow, the less efficient the system. The experimental work procedures are carried out as the following procedures in order:

1. Before doing any experimental measurements, the experiment is prepared carefully before starting the reading, checking electrical joints of the heaters, measuring instruments and temperature control unit.
2. In the first stage of operation, we operate the oil heating system and leave it working until the water temperature is raised to the required degree.
3. During the operation of the oil heating system, there must be a person standing in front of the control panel to control the switch for the induction heaters so that each two balls work only two minutes and then separate two minutes and during the separation the other two balls work alternately so as not to burn.
4. After the water temperature reaches the appropriate degree, we turn on the blower on the needed flow and the cooling system together and then look a little bit until the cooling system becomes stable.
5. Then we open the water spray pump on the needed flow to make the humidifier work.
6. The collected yield freshwater quantity of the two stills is measured carefully and registered.
7. Repeat the previous two procedures (4 and 5) each time step reading.
8. At the end of all-day readings, preparing the solar still system as the first reading day (ensure that the glass cover and PV surface are clean, all insulated system parts are well insulated to prevent leakage, etc.), and then do the procedure 1 to do the next day readings.

## 4. Error Analysis

Errors and uncertainties in the experiments can arise from instrument selection, condition, calibration, environment, observation, reading and test planning. It is very important to estimate the accuracy of the measured and calculated parameters in order to make a correct analysis of the experimental results. The measured parameters include temperatures, solar radiation, wind velocity and productivity. Also, the calculated parameters include instantaneous efficiency for the still. Holman (Holman, et al, 1994) used a method to estimate the uncertainty in experimental. The uncertainty in the measurements is defined as the root sum square of the fixed error of the instrumentation and the random error observed during different measurements. The uncertainty in the results W_R is calculated as:

$$W_R = \sqrt{(\frac{\partial R}{\partial X1} W_1)^2 + (\frac{\partial R}{\partial X2} W_2)^2 + \cdots + (\frac{\partial R}{\partial Xn} W_n)^2} \quad (5)$$

Where W1, W2, W3 ............ Wn are the uncertainties in the independent variables. A set of measurements is done in order to measure "n" number of experimental variables. These measurements are used to calculate some desired results of the experiment. Table 5 shows the accuracy, range and percentage error for various instruments used. All values are small compared to the data obtained and found to be within the allowable range of the measurements of the devices. Accordingly, the resulting errors of the calculated amount of gain output ratio is ± 1.008 %.

**Table 5. Accuracy and error for various measuring instruments.**

| No | Instrument | Accuracy | Range | % Error |
|---|---|---|---|---|
| **1** | Thermometer | ±1 °C | 0 – 100 °C | 1% |
| **2** | Thermocouple | ±0.1 °C | -270 – 1820 °C | 0.005% |
| **3** | Solar watt meter | ±1 W/m2 | 0 – 2500 W/m2 | 0.04% |
| **4** | Anemometer | ±0.1 m/s | 0 – 12 m/s | 0.83% |
| **5** | Measuring flask | ±10 ml | 0 – 1000 ml | 1% |

## 3. Results and discussion

**Figure 4** illustrates the fresh water production over the day, comparing different opening settings for air intake while maintaining a constant air flow rate of 252 kg/hr. Results reveal that larger openings lead to significantly higher water production, particularly around noon, due to increased air intake volume. For instance, the full open setting produces around 6.96 L/hr at its peak, compared to only 2.22 L/hr for a half-open setting. This behavior suggests that a higher air intake volume increases humidification efficiency, enhancing the air's capacity to carry water vapor for condensation. The peak production observed around midday correlates with the period of maximum solar irradiance, highlighting the system's reliance on both air flow and solar energy for optimal productivity.

In Figure 5, the Gain Output Ratio (GOR) is presented for varying open settings under a fixed air flow rate of 252 kg/hr. The GOR increases significantly with a wider open setting, achieving a peak of 1.18 for the full open setting at midday, compared to a peak of 0.46 for the half-open setting. These results show that maximizing air flow volume not only enhances fresh water production but also improves the system's energy efficiency by better converting available thermal energy into fresh water. This increase in GOR indicates that more of the system's energy is effectively utilized for water production, particularly during high solar radiation periods, thereby improving overall system efficiency.

**Figure 6** presents hourly fresh water production for different air flow rates with a constant, fully open setting, emphasizing the critical role of air flow rate in fresh water output. The production rate increases markedly with higher air flows, reaching up to 17.64 L/hr for an air flow of 504 kg/hr during peak hours. By contrast, an air flow rate of 252 kg/hr results in a maximum production of only 6.96 L/hr. The improved fresh water yield at higher air flows can be attributed to more effective humidification, which allows the air to carry a larger volume of vapor to the condenser, thus maximizing condensation efficiency. The midday peak also aligns with solar irradiance, showing the combined impact of air flow and environmental heat.

Figure 7 shows the GOR across different air flow rates while maintaining a fully open setting. The GOR is highest at an air flow rate of 504 kg/hr, reaching a peak value of 2.98 around midday. At a lower flow rate of 252 kg/hr, the GOR peaks at only 1.18. This comparison demonstrates that increased air flow not only raises fresh water output but also enhances energy efficiency, indicating that the system more effectively utilizes available energy. The higher GOR values during peak solar hours further suggest that the system's thermal input from solar radiation is optimally harnessed, particularly under conditions of high air flow.

**Figure 8** depicts the cumulative fresh water production over the day for different air flow rates, all with a full open setting. The total daily fresh water production is significantly greater at higher air flows, reaching approximately 141.1 L at 504 kg/hr, compared to only 55.6 L at 252 kg/hr. This cumulative output underscores the importance of higher air flow rates, which support more continuous and effective humidification and condensation processes. The figure also highlights that, while production is highest during midday due to peak solar irradiance, high air flow rates sustain productivity throughout the day, allowing the system to maximize daily fresh water yield.

The figures collectively underscore the interplay between air flow rate, open setting, and solar irradiance in optimizing the humidification-dehumidification system's fresh water production and energy efficiency. Figures 4 and 5 demonstrate that at a constant air flow rate, a wider opening setting enhances both fresh water yield and GOR, suggesting that increased air intake volume improves humidification. Figures 6 and 7 shift focus to air flow rate at a fully open setting, revealing that higher air flows lead to substantially increased fresh water production and GOR values. Lastly, Figure 8 consolidates this understanding by showing that high air flows sustain high productivity throughout the day, maximizing cumulative fresh water yield. Together, these figures illustrate that optimal performance is achieved by balancing high air flow rates with a fully open setting, particularly under conditions of peak solar irradiance.

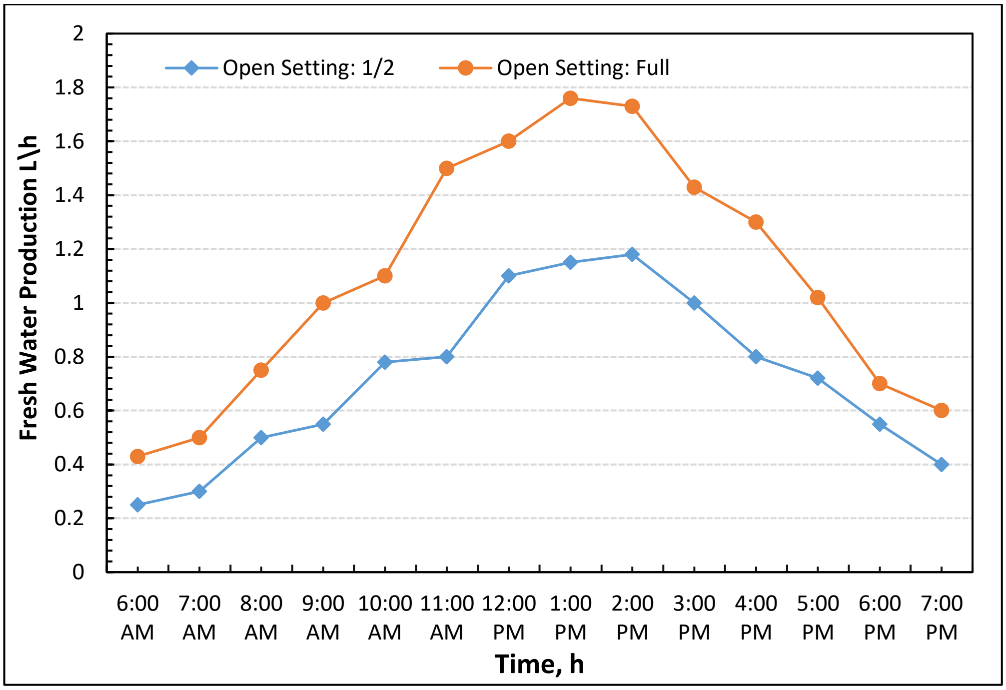



**Figure 4: Hourly fresh water production at different open setting and constant air flow rate 252 kg/hr**

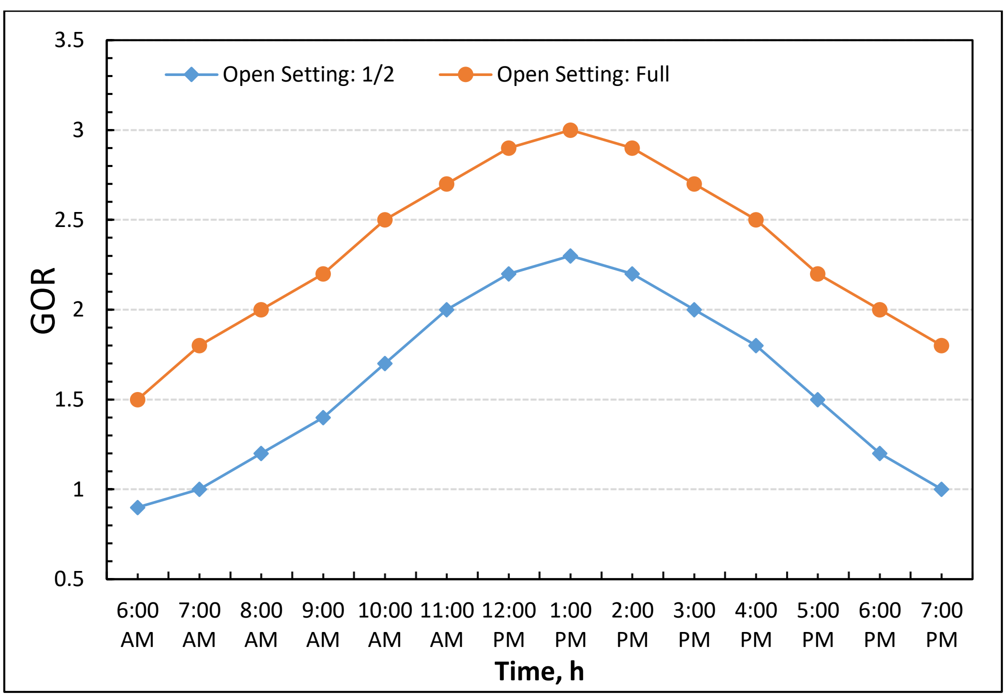



**Figure 5: Hourly GOR at different open setting and constant air flow rate 252 kg/hr**

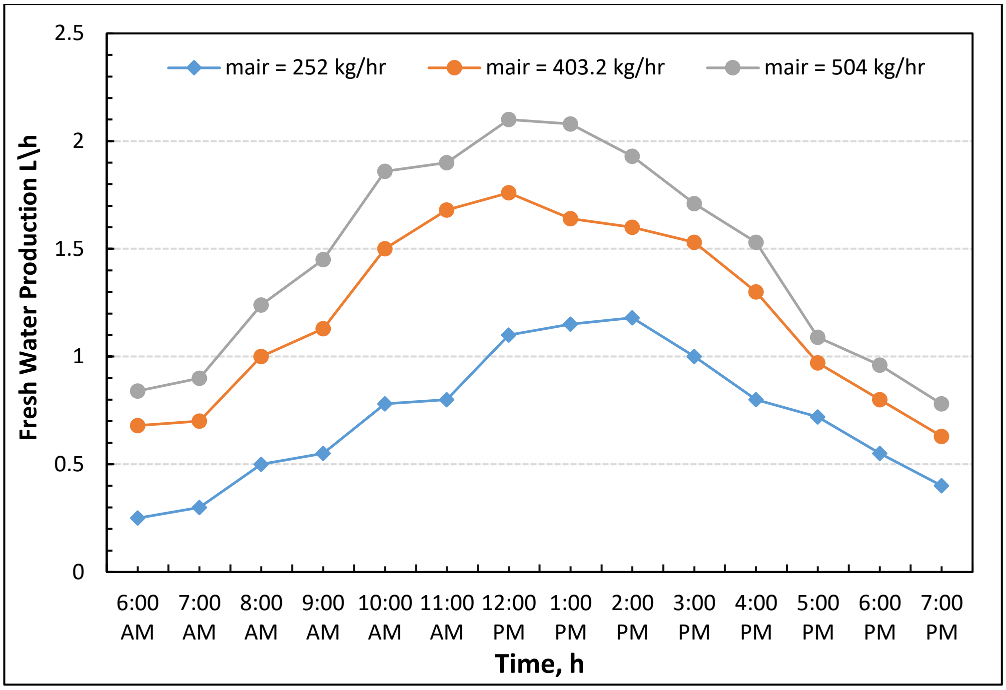



**Figure 6: Hourly fresh water production at different air flow rate and constant open setting at full**

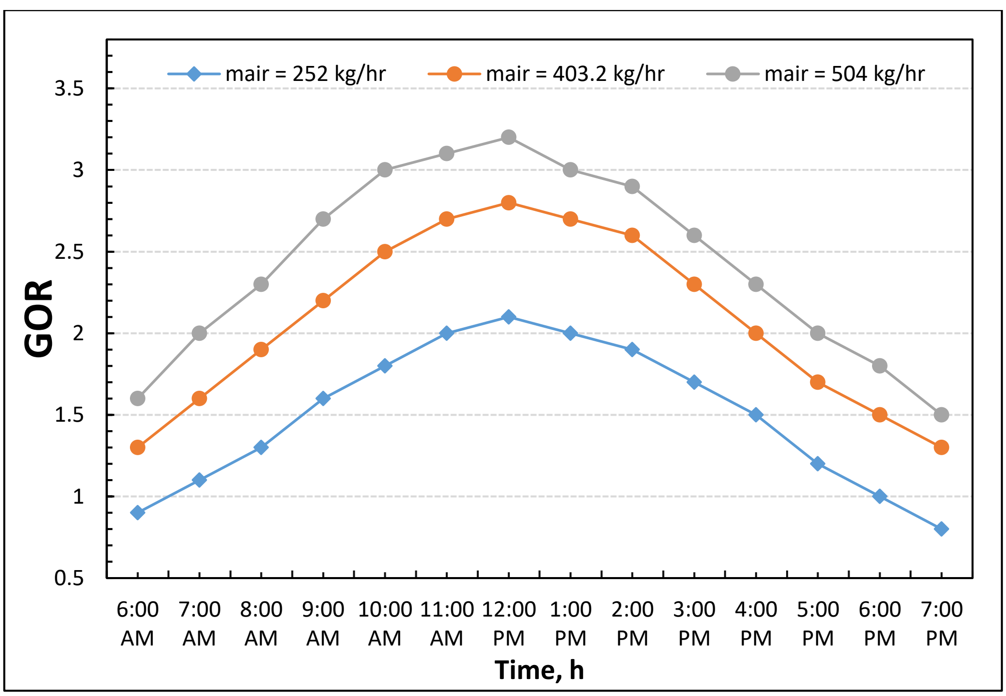



**Figure 7: Hourly GOR at different air flow rate and constant open setting at full**

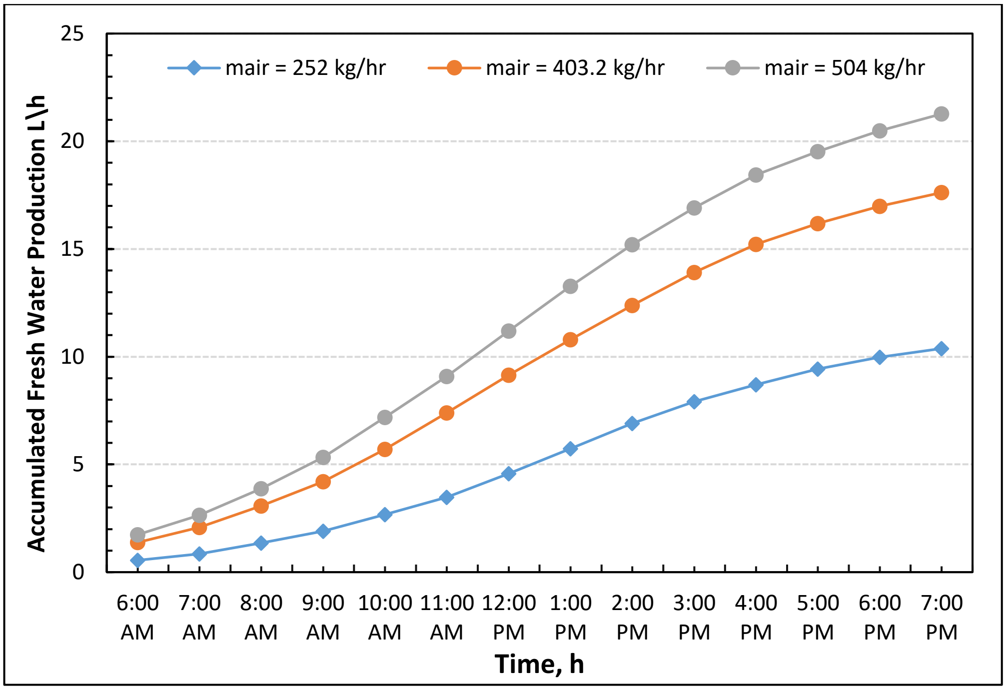



**Figure 8: Accumulative fresh water production at different air flow rate and constant open setting at full**

The cost analysis for the solar-powered HDH system shows that while the initial capital expenditure is significant, the long-term costs can be relatively low due to the minimal operating costs associated with solar energy. The major recurring costs are associated with maintenance and auxiliary power for the pumps and blowers. The calculated cost of water production is competitive with other desalination methods, especially when considering the environmental benefits of using solar energy. However, the actual cost may vary based on several factors, including local solar irradiance, cost of materials, labor rates, and the scale of production. Further optimization in system design, such as improving the efficiency of the solar collectors or integrating advanced materials in the humidifier and dehumidifier, could further reduce costs.

Using the following formulas, the cost per liter for the HDH system can be calculated:

Cost per liter = $\frac{Total\ Cost}{Total\ Volume\ of\ Water\ Produced\ per\ Hour\ \times Operational\ Hours\ Per\ Year}$

Cost per liter = $\frac{2286.08}{17.64 \times 3600} = 0.029\$$

Given:

- Total Cost = \$2286.08
- Total Volume of Water Produced per Hour = 17.64 liters/hour

Thus, the cost per liter is approximately:

- Cost per Liter = 0.029 \$ per liter

This cost per liter is based on a specific operational period. By adjusting the system's operational hours, the cost per liter can be recalculated according to the desired output duration and water production.

## 4. Conclusion

This study explored the performance of a humidification-dehumidification (HDH) desalination system utilizing waste heat from a refrigeration unit and a secondary induction heating unit to enhance the desalination process. The experimental setup demonstrated the system's ability to desalinate highly saline water efficiently, producing high-quality freshwater with minimal pollutants or salt content.

- The system reaches its highest water production of 17.64 L/hr at an air flow rate of 504 kg/hr with a fully open setting, especially around noon. Lower air flow rates, such as 252 kg/hr, produce only 6.96 L/hr, showing that high air flow is essential for greater water output.

- A fully open setting with high air flow results in a peak GOR of 2.98, indicating efficient energy use. By comparison, a half-open setting lowers GOR to just 1.18, showing that a full opening improves overall efficiency.

- With a fully open setting and 504 kg/hr air flow, the system produces around 141.1 L of fresh water per day. This is over twice as much as the 55.6 L produced with a 252 kg/hr air flow, showing that higher air flow supports consistent water output.

- Peak water production and efficiency around midday emphasize the importance of sunlight. High air flow during peak sunlight hours maximizes system performance.

- Highest GOR values occur at high air flow rates, showing that the system uses energy best with full openings and peak sunlight

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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